



# Autonomous Spacecraft Communication Interface for Load Planning

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## **Abstract**

Ground-based controllers can remain in continuous communication with spacecraft in low Earth orbit (LEO) with near-instantaneous communication speeds. This permits near real-time control of all of the core spacecraft systems by ground personnel. However, as NASA missions move beyond LEO, light-time communication delay issues, such as time lag and low bandwidth, will prohibit this type of operation. As missions become more distant, autonomous control of manned spacecraft will be required. The focus of this paper is the power subsystem. For present missions, controllers on the ground develop a complete schedule of power usage for all spacecraft components. This paper presents work currently underway at NASA to develop an architecture for an autonomous spacecraft, and focuses on the development of communication between the Mission Manager and the Autonomous Power Controller. These two systems must work together in order to plan future load use and respond to unanticipated plan deviations. Using a nominal spacecraft architecture and prototype versions of these two key components, a number of simulations are run under a variety of operational conditions, enabling development of content and format of the messages necessary to achieve the desired goals. The goals include negotiation of a load schedule that meets the global requirements (contained in the Mission Manager) and local power system requirements (contained in the Autonomous Power Controller), and communication of off-plan disturbances that arise while executing a negotiated plan. The message content is developed in two steps: first, a set of rapid-prototyping “paper” simulations are preformed; then the resultant optimized messages are codified for computer communication for use in automated testing.

## **1.0 Introduction**

As manned spacecraft travel further from Earth, light-time communication delays will make the present ground-based mission control unworkable (Ref. 1). To enable distant missions, NASA has begun investigating architectures that will provide autonomous control of the spacecraft (Refs. 1 and 2). Currently, controllers develop a complete schedule for all spacecraft components (e.g., Electric Power System (EPS), Thermal Management, Communications, Environmental Control and Life Support Systems); much of this schedule is created by humans on the ground running software tools to analyze the subsystem for which they are responsible (Refs. 3 to 5).

For the case of the electric power system onboard the International Space Station, the planning process involves teams at three different locations (Ref. 5). In addition to solving the planning problem, controllers on the ground respond to disturbances and faults that may occur in each of the subsystems. In

order to enable autonomous operation, all of this functionality must be implemented onboard. Unfortunately, it is neither realistic nor useful to require that the flight crew gain expert knowledge of all vehicle subsystems. Thus, the control software must be capable of responding to these situations through an autonomous or semi-autonomous decision-making process.

This paper presents an early attempt to formalize and automate the processes of planning the power system load scheduling, and responding to disturbances in the plan or plan constraints, using on-vehicle computation resources. The main focus is on development of a communication scheme between two key spacecraft components: the Mission Manager (MM) and the Autonomous Power Controller (APC).

Section 2.0 provides a high-level overview of the proposed autonomous spacecraft control architecture, the MM, the APC, and the test power system. Section 3.0 describes the process used for development of the communication format for the messages between the MM and the APC. Conclusions are presented in Section 4.0.

## 2.0 Autonomous Spacecraft Control Architecture

This section briefly describes the Autonomous Spacecraft Control Architecture discussed more fully in Reference 6. Two key subsystems, the MM and the APC, are also described, as is the power system under test.

A potential autonomous spacecraft controller architecture is shown in Figure 1 (Ref. 6). In this architecture, the MM is responsible for the high level control functions (e.g., planning), while each of the subsystems features an autonomous controller (e.g., Autonomous Power Controller, Autonomous Thermal Controller, etc.) which interfaces with the respective subsystem hardware. As previously mentioned, this work focuses on developing the communication protocol between the MM and the APC, both highlighted in green.

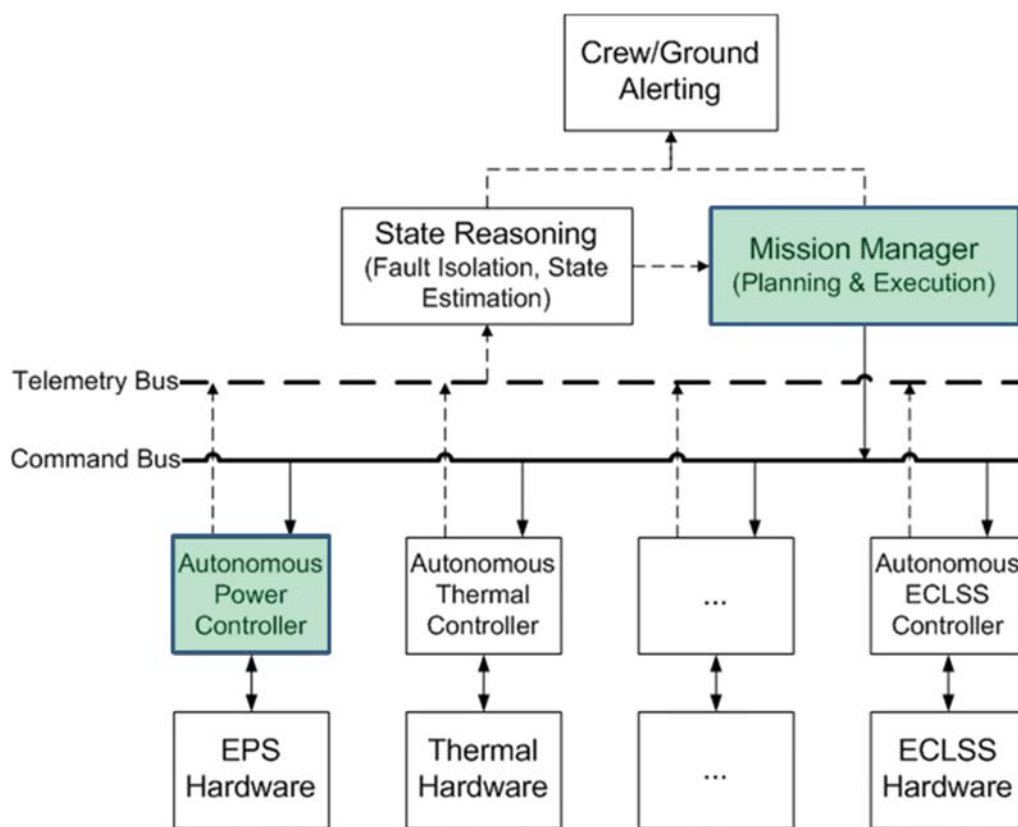


Figure 1.—Autonomous spacecraft controller architecture.

## **2.1 Mission Manager Overview**

The spacecraft MM is responsible for coordinating the various subsystems, as well as managing crew time to achieve mission objectives. From the power system perspective, the most important global issue is load scheduling (creating a timeline of when loads are in use and their associated priority). However, because the vehicle-level optimal planning problem is highly complex, a key goal of this system is to limit the amount of subsystem detail the MM is required to know. Thus the spacecraft's MM must work in concert with the APC (where the EPS subsystem detail is located) to develop a load schedule based on mission priorities, as well as inputs that it has received from the other autonomous subsystems. Due to the fact that the MM has a global perspective of vehicle status, it is able to diagnose and provide recommendations regarding faults that affect more than one subsystem (Ref. 7).

## **2.2 Autonomous Power Controller Overview**

While the vehicle MM is responsible for strategic planning and coordination of all subsystems, the autonomous subsystem controllers such as the APC are responsible for operating the subsystem in the manner most consistent with the strategic plan. The APC directly interfaces with the Electrical Power System (EPS) hardware, as shown in Figure 1, and has detailed knowledge of the electrical power system. This detailed knowledge (e.g., available power, energy storage capacity, operating modes, etc.) allows the APC to work in tandem with the MM to solve the relevant vehicle planning problem (i.e., develop a feasible a load schedule). The APC also manages local control issues, and reports them to the spacecraft MM.

## **2.3 Example Power System**

The communication developed in this paper is not tied to any specific vehicle power system. It can be applied to any power system type. Typically, such a power system will contain four main components: power generation, energy storage, a switchable network, and electrical loads.

In order to conduct the load planning exercises performed in this paper, it was necessary to define vehicle power system architecture. The selected architecture includes solar arrays for power generation, batteries for energy storage and a switchable network architecture as described in Reference 7. Also, a set of 30 notional loads was defined, and their corresponding power consumption was arbitrarily constructed. An eclipse/insolation period of 30/60 min was assumed.

One key objective of this type of controller is to minimize lower level knowledge required by higher level systems. However, note that some key information must be held common by both the MM and the APC. In this case, this common information includes the list of loads, the load numbers, and the power usage for each load.

## **3.0 Communication Development**

This section includes an overview of the communication required between the MM and the APC, describes the rapid-prototype “paper” simulations performed, provides details of the test cases run, and provides the resultant automated communications message format.

### 3.1 Communications Overview

The purpose of this message development exercise is to define a communication protocol between the MM and the APC, which can be automated and allows the two subsystems to work in tandem to achieve the desired goals. The goals of this communication exchange are to enable the two systems to:

1. Work together to negotiate a feasible load schedule that maximizes the mission objectives achieved by the vehicle.
2. Communicate, and then adapt to, any unexpected deviation from the agreed-upon plan.

To achieve the goals above, two separate classes of communication have been defined: Planning Communications and Asynchronous Communications.

*Planning Communications* are used to negotiate a load schedule. They are always initiated by the MM, and are used to negotiate a load schedule which is feasible and with appropriate priority (defined by the MM), based on the power system availability (defined by the APC). The negotiated load schedule must meet global requirements at the MM level, while utilizing local detailed system information (e.g., line capacity, state of charge, network configuration, etc.) at the APC level to ensure that no power system constraints are violated. The resulting load schedule lists the state and priority of each load in the system at discrete time intervals over a defined planning window. This schedule may then be executed upon request by the vehicle MM.

*Asynchronous Communications* are used when a disturbance arises while executing a previously negotiated plan. They are always initiated by the APC outside of the typical planning cycle. These messages may be sent in case of component failures, system failures, or any other unexpected change in a system operating state or constraint. For the purposes of this document, only disturbances to the load plan and unanticipated changes in power availability are considered; component and system failures will be addressed in future work.

A high-level overview of the tasks which must be accomplished during Planning and Asynchronous Communications is listed below.

#### 3.1.1 Planning Communications Cycle

1. *Initiate Planning*: At the initialization of the planning process, the MM informs the APC of the proposed planning period start time, end time, and time step.
2. *Define Power Constraints*: The APC then uses the above data as well as its knowledge of the system status to compute the nominal and peak power availability at each time step of the planning window, and the peak energy available during the planning window. The APC sends this information, along with any load power constraints, back to the MM.
3. *Define Load Schedule*: The MM then uses this power, energy, and constraint information, along with crew status and information from other subsystems, to develop a proposed vehicle plan. One component of this plan is a schedule of load power utilization and priority, for each load in the system, which is then communicated to the APC.
4. *Determine Feasibility*: The APC performs power flow calculations and contingency analyses to determine the feasibility of the proposed load plan at each time step of the planning window. For any point at which the plan is found to be infeasible, the APC will determine which of the load profiles are in conflict and inform the MM. The planning process will iterate until the MM and APC have converged on a satisfactory plan.
5. *Decision (Re-plan or Implement)*: Finally, the MM either commands the APC to implement the negotiated plan at the appropriate start time, or informs the APC of its intention to develop a new plan. The MM can ask the APC to implement any plan, regardless of feasibility; however, if the APC is tasked with implementing an infeasible load plan, load will be shed to force the system to remain within operational constraints.



### 3.1.2 Asynchronous Communications Cycle

Note that the communication necessary to handle these events is inherently unplanned.

1. *Inform of Disturbance*: Upon detection of a disturbance, the APC will determine the impact of the disturbance on its capability to operate as specified during the currently executing plan. This information, which is key to determining if a replan is necessary in order to maximize the vehicle's mission objectives, is passed to the MM.
2. *Decision (Re-Plan or Implement)*: The MM then decides whether a replan is necessary. If so, the planning process is started via a Planning Communications Cycle, with the disturbance accounted for as a new constraint.

## 3.2 Paper Simulation

The initial development of communication messages between the MM and the APC was accomplished using “paper simulations.” These paper sims utilized spreadsheets to generate messages, and email to transmit them between the MM (being developed at NASA Ames Research Center, in California) and the APC (being developed at NASA Glenn Research Center, in Ohio). In this manner, a number of complete planning sessions (Planning Communications Cycles) and disturbance identification and rectification sessions (Asynchronous Communications Cycles) were completed. This approach was taken to accomplish two goals: to accelerate communication message development, and to allow quick refinement of the relevant message content.

At the time of the message format development, only prototype versions of the MM and the APC existed. These prototypes performed the relevant functions of the respective subsystems, but they were not yet automated—they only worked with a human in the loop. One obvious advantage of the paper sim approach was speed: by initiating paper simulations early on, the teams did not have to wait until automation of MM and APC functions was complete, thus accelerating development. Additionally, the messages developed during the paper sim drove the requirements of the automated software algorithms.

Since entire Planning and Asynchronous Communication cycles were rapidly completed via the paper sims, lessons about which message content is relevant and which is superfluous were quickly learned. Use of spreadsheets, with easily variable content and format, along with email and phone communication between development teams allowed rapid evolution of message content, allowing messages to quickly be reduced to a thorough, yet efficient, format. This refinement allowed many details of the message content to be finalized early in the development cycle, where changes and updates are least expensive in terms of effort and schedule.

### 3.2.1 Test Cases

Throughout the paper sim, planning simulations were conducted under a variety of test conditions, in order to verify that the messages under development contained the necessary format and content to achieve the desired goals under any reasonable set of conditions.

During Planning Communications development, sims were performed under a number of power system constraints: with imposed battery state of charge (SOC) limits, solar array (photovoltaic, or PV) output limits, PDU current output (single or multiple) limits, battery current limits, and line current limits.

Disturbances introduced during development of Asynchronous Communications included unexpected load operation (loads on longer or shorter than expected, with varied impacts on the existing Plan), loads drawing less power than planned, and sources providing less power than planned.

The details of the paper sim testing conditions are summarized in Table 1.

TABLE 1.—PAPER SIM COMMUNICATION TESTING CONDITIONS

Planning Test	Implementation	Sim Tested	Details
1	Battery SOC within limits	Sim #1 - 13	Constraint captured by peak power availability & energy availability
2	PV Output < limit	Sim #1 - 13	Constraint captured by power availability
3	Limit one PDU power	Sim #3	Limit PDU 5 to 2kW
4	Limit multiple PDUs	Sim #4	PDU 1-4 limited to 425W switchable global
5	Limit line current	Sim #6	Limit line current from SA 1
6	Limit battery current	Sim #5	Limit Batteries to 83 A (10kW, down from 133A/32kW). Battery 1 global, battery 2 temporary.
7	Temporary PDU power constraint	Sim #4	PDU 7 limited for 1 interval
Asynch Test	Implementation	Sim Tested	Details
1	Load on for too long - no impact in planning period	Sim #8	Load 13 on beyond scheduled period - should have turned off at 4:30
2	Load on for too long - impact during planning period	Sim #11	Load 12 remained on beyond scheduled period - should have turned off at 2:30
3	Load on for too short	Sim #9	Load 5 off 30 mins early
4	Load on for too short - additional power available significant, thus opportunity	Sim #13	Loads 12 and 14 turned off early (expected them to be on until 2:30)
5	Actual load < est load - additional power available insignificant	Sim #10	Load 26 drawing less power than planned (expected 700W, drawing 550W)
6	PV array output < est output - requiring replan	Sim #12	Output from Solar Array 1 lower than expected

TABLE 2.—DETAILS OF P1 COMMUNICATION

P1 #12 26-Mar-14		
start time	end time	delta T (min)
12:00	10:30	30

### 3.2.2 Planning Communications Cycle

During the course of the paper simulations, five messages were developed for a typical planning session. These are designated P1 through P5.

#### 3.2.2.1 Initiate Planning (P1)

The P1 is initiated by the MM to start the planning process. Along with a header defining the message type, simulation number, and date (typical of all paper simulation communications), the P1 specifies the planning horizon: start time, end time, and time step (delta T). It is important to note that the delta T used in the planning process is dependent upon both vehicle and power system time scales of interest, particularly eclipse/insolation periods. Details of the P1 communication are shown in Table 2.

### 3.2.2.2 Define Power Constraints (P2)

The P2 is the APC's response to a P1 message from the MM. In addition to the header, the P2 contains nominal and peak power available for each time step in the planning window, as well as peak energy available to the MM during the course of the planning window. Also, any known constraints (temporary or global) on the system are also communicated. Constraints are formulated as the sum of loads must not exceed some power level. All power system constraints considered in the paper simulations are able to be constructed in such a manner. Note that this approach requires that both systems have common understanding of loads and load IDs. A distinction is made between "local" constraints, those active only during some planning intervals, and "global" constraints, those active during all intervals in the current planning window.

Nominal power is the amount of power available given that the storage devices in the system are charging at a constant rate for the entire insolation period. During eclipse periods, the nominal power is the amount of power that the storage devices can supply to the system for the entirety of the eclipse without exceeding state-of-charge requirements. The Peak power considers that all generation devices are outputting at maximum for the time period. Thus, imbedded in this number are device power output constraints as well as each generator's time-varying capability.

If the power utilization (as defined by the load profile) is greater than the nominal power available, then the storage devices will be used to meet the excess load requirements. The result of this is that the storage cannot be charged and/or will deviate from the nominal state-of-charge range. To allow the MM to wisely use this capability, the total energy availability of the storage devices is given by the APC (in Watt-hours). The MM is then responsible for tracking the amount of peak power utilized as well as the duration used; the sum of the peak energy used for all time periods must be less than the peak energy available as provided by the APC. Details of the P2 communication are presented in Table 3.

### 3.2.2.3 Define Load Schedule (P3)

The P3, initiated by the MM in response to the P2, contains the proposed load schedule, developed based on the provided power profile. In addition to the header, the message contains a load status and priority for every load at each time step in the planning period.

For this study, all loads are either "off" or "on" (both systems have shared info as to how much power each load uses when on and off). Thus, both the state and priority of each load can be encoded in a single value, either "off" or a priority number. Here, the lower the priority number, the higher the priority of the load. Details of the P3 communication are presented in Table 4.

TABLE 3.—DETAILS OF P2 COMMUNICATION

P2 #12 26-Mar-2014			
time	Pnom (W)	Ppeak (W)	constraints
12:00	6008	45968	
12:30	6008	45968	
...	...	...	...
3:30	6008	45968	
4:00	5984	21968	loads 4,8,25,27,29 combined must not exceed 60W
...	...	...	...
5:30	5984	21968	loads 4,8,25,27,29 combined must not exceed 60W
6:00	6008	45968	
...	...	...	...
9:30	6008	45968	
10:00	5984	21968	
peak energy avail (Wh)	8000		
			Global Constraint: Loads 1, 19 and 23 combined must not exceed 360 W

TABLE 4.—DETAILS OF P3 COMMUNICATION

P3 #12 26-Mar-2014				
	12:00:00 AM	12:30:00 AM	...	10:00:00 AM
load	Priority	Priority	...	Priority
1	off	off	...	off
2	off	12	...	off
3	off	off	...	off
...	...	...	...	...
29	41	41	...	off
30	off	off	...	22

TABLE 5.—DETAILS OF P4 COMMUNICATION

P4 #9 18-Mar-2014	
time	status
12:00	able to meet
...	...
9:30	Loads 1, 4, and 9 must not exceed 500W
10:00	able to meet

TABLE 6.—DETAILS OF P5 COMMUNICATION

P5 #12 26-Mar-2014
"Implement Plan"

### 3.2.2.4 Determine Feasibility (P4)

The P4, initiated by the APC in response to the P3, determines feasibility of meeting the proposed load schedule. In addition to the header, the P4 contains a status at each time step of the planning period, communicating whether or not the power system can meet the load schedule. If the system cannot meet the proposed schedule, the message describes the nature of the conflict. Again, any constraint will be formulated as the sum of loads must be less than some power level. Details of the P4 communication are presented in Table 5.

### 3.2.2.5 Re-Plan or Implement (P5)

The P5 message, initiated by the MM, commands the APC to implement the proposed plan in the event that the P4 stated “able to meet” at all-time steps. Otherwise the MM will rework the schedule, which is done by recalculating, then sending out a new P3. Details of the P5 communication are presented in Table 6.

An “Implement Plan” P5 message concludes a successful planning session.

## 3.2.3 Asynchronous Communications Cycle

Two different asynchronous messages were developed during the course of the paper simulations: the A1 and the A2.

### 3.2.3.1 Inform of Disturbance (A1)

The A1 message is initiated by the APC in the event of a disturbance to the power system or a deviation in the system that impacts a parameter used during load planning. In addition to the header, it contains the time of occurrence, the nature of the disturbance, and the impact on the schedule. Schedule impact is described by the time, within the planning window, at which the disturbance will prevent the power system from meeting the negotiated schedule. If the disturbance causes no impact to the schedule, no time is provided. Details of the A1 communication are presented in Table 7.

TABLE 7.—DETAILS OF A1 COMMUNICATION

A1 #12 26-Mar-2014		
Time	Disturbance	Impact
3:05	Output from Solar Array 1 lower than expected	"No impact within planning period" or "Will exceed peak power allotment by 3:27"

TABLE 8.—DETAILS OF A2 COMMUNICATION

A2 #12 26-Mar-2014	
"Replan Required" or "No Action Required"	

### 3.2.3.2 Re-Plan or Implement (A2)

The A2 message is initiated by the MM in response to an A1. In addition to the header, the A2 communicates response to the disturbance: "No Action Required", or "Replan Required". Details of the A2 communication are presented in Table 8.

## 3.3 Automated Communications Format

The final step in the development of the communication format was to convert each message into a computer readable format, to enable these messages to be sent and processed by automated software. Since we were not overly concerned with message bandwidth at this early development stage, a bit-level encoding was not necessary. Additionally, coding the messages as character arrays allows them to be processed by software, while maintaining human readability, which will be helpful during testing.

The protocol over which the messages are to be sent is not particularly important at this time, and thus TCP sockets are used. Whitespace and line breaks included in the messages shown below are simply for human readability and are stripped from both incoming and outgoing messages.

Note that the messages use a 24 hr clock; thus use leading zero if applicable (hh:mm). Also, text is not case-sensitive for the receiver, but is standardized for the automated sender: capitalize first word only.

Pseudo-code describing the decision logic for message handling, from the MM and the APC perspective, is provided below.

#### 1. MM Message Handling Pseudo-code:

```

If START
  then send P1 message
  else if receive P2 message
    then send P3 message
    else if receive P4 message
      then if P4 message has no violations
        then send P5 message (Implement)
      else resend P3 with the new constraints from P4 taken into account

```

#### 2. APC Message Handling Pseudo-code:

```

If receive P1 message
  then send P2 message
  else if receive P3 message
    then send P4 message
  else if receive P5 message
    then Implement

```

Details of the developed Automated Communications Format messages, for the Planning and Asynchronous Communications, are included in the following sections.

### 3.3.1 Planning Communications Cycle

Automated formats for the five messages comprising a typical Planning Communications session are described below.

#### 3.3.1.1 Initiate Planning (P1)

Time recording is based on the ISO-8601 standard. All times are UTC. Since we've decided the minute is our lowest resolution, no seconds are required. It is assumed that the planning horizon is limited to 24 hr, to prevent ambiguity. Note that the "final time" is defined as the end of the Planning period, not as the beginning of the last interval. Thus if the planning period was defined as 01:00 to 02:00 with a step of 30 min, there would be two steps in the period; one from 01:00 to 01:30, and one from 01:30 to 02:00.

Details of the automated P1 message are presented in Table 9.

#### 3.3.1.2 Define Power Constraints (P2)

Constraints are formatted as 'The sum of load power consumption must be less than some value in watts'. To encode this, each of the load power consumption values is replaced by the load ID# to produce: "4+8+25<60" which is read as the sum of the power used by loads 4, 8, and 25 must be less than 60W. The "+" signs are markers between each of the load IDs, and the "<" sign is the demarcation of the load IDs from the power limit. If multiple local constraints (constraints limited to a subset of the planning window) exist at a single time step, they will be separated by commas. If multiple global constraints exist, they will be listed on separate lines. Details of the automated P2 message are presented in Table 10.

#### 3.3.1.3 Define Load Schedule (P3)

Note that 0 is a valid priority, and is the highest priority possible, so use of a "0" to indicate the load is in the "off" state is not practical. Thus loads in the off state are designated by just a comma. Details of the automated P3 are presented in Table 11.

#### 3.3.1.4 Determine Feasibility (P4)

Will send content only for violation time steps. Details of the automated P4 message are presented in Table 12.

#### 3.3.1.5 Decision: Re-Plan or Implement (P5)

The MM will simply send an "Implement" command. Another option is to command "save with a name", but that feature will not be implemented for this simulation. Details of the automated P5 message are presented in Table 13.

TABLE 9.—DETAILS OF P1 COMMUNICATION

Message	Format	Example
P1	<u>Format:</u> initial time, final time, delta t (minutes);	<P1> 2014-04-01T12:00, 2014-04-01T19:30, 30; </P1>

TABLE 10.—DETAILS OF P2 COMMUNICATION

Message	Format	Example
P2	T (hh:mm), Pnom, Ppeak, Constraint; ... Wh, peak energy available; global constraint;	<P2> 12:00, 6008, 45968,; ... 14:00, 6008, 45968, 4+8+25+27+29<60; ... Wh, 8000; 3+7+26+28<1500; </P2>

TABLE 11.—DETAILS OF P3 COMMUNICATION

Message	Format	Example
<b>P3</b>	, T0, T1, ..., Tn; Load #, time interval 1 priority, . . . , time interval n priority; ...	<P3> , 12:00, 12:30, . . . , 19:00; 1, . . . , 14, 18, . . . , ; 2, . . . , 24, . . . , 48, . . . , ; 30, . . . , 18, . . . , 21, . . . , ; </P3>

TABLE 12.—DETAILS OF P4 COMMUNICATION

Message	Format	Example
<b>P4</b>	Time (hh:mm), new constraint; ...	<P4> 18:30, 3+4+5+6<60; </P4>

TABLE 13.—DETAILS OF P5 COMMUNICATION

Message	Format	Example
<b>P5</b>	Implement;	<P5> Implement; </P5>

TABLE 14.—DETAILS OF A1 COMMUNICATION

Message	Format	Example
<b>A1</b>	<u>Format:</u> Timestamp, disturbance, impact horizon;	<A1> 15:03, There was a disturbance,; 14:35, There was a disturbance, 14:53; </A1>

TABLE 15.—DETAILS OF A2 COMMUNICATION

Message	Format	Example
<b>A2</b>	<u>Format:</u> No action;	<A2> No action; </A2>

### 3.3.2 Automated Asynchronous Communications Cycle

Automated formats for the two messages comprising a typical Asynchronous Communications session are described below.

#### 3.3.2.1 Inform of Disturbance (A1)

In the event of a disturbance, the A1 is sent from the APC to the MM. Details of the automated A1 message are shown in Table 14.

#### 3.3.2.2 Decision: Re-Plan or Implement (A2)

Details of the automated A2 message are presented in Table 15.

## 4.0 Conclusions

This paper describes the development of a communication scheme between two key systems in an autonomous control system for a manned deep space vehicle. The focus of the effort is the electrical power subsystem. A nominal spacecraft power system architecture was described, and prototype versions of these two key systems, the Mission Manager (MM) and Automated Power Controller (APC), were constructed.

To develop the communication messages, first a set of rapid-prototyping “paper” simulations were run, simulating communication between the MM and the APC under a variety of operational conditions. These paper sims enabled development of message content and format necessary to achieve the desired goals: negotiation of a load schedule that meets the global vehicle and local power system requirements, while enabling communication of off-plan disturbances that arise while executing a negotiated plan. Once these messages were optimized, and shown to perform well under nominal and off-nominal conditions, they were codified for computer communication, for use in automated testing. A summary of the communication formats developed in this paper is included in the Appendix.

Future work in this area includes the addition of more complex disturbances, such as failures, and testing on a hardware system.



## Appendix—Summary of Automated Communication Formats

A summary of the Automated Communication Formats for Planning and Asynchronous communication is included in Tables 16 and 17.

Table 16. Summary of the Automated Communication Format between the MM and APC to develop a load schedule.

Message	Initiator	Receiver	Purpose	Content	Format	Example
P1	MM	APC	Initiate Planning	Planning period start time, end time, time step	Format: initial time, final time, delta t (minutes);	<P1> 2014-04-01T12:00, 2014-04-01T19:30, 30; </P1>
P2	APC	MM	Define Power Constraints	Nominal and peak power for each time step, peak energy available for planning period, other power constraints	T (hh:mm), Pnom, Ppeak, C constraint; ... Wh, peak energy available; global constraint;	<P2> 12:00, 6008, 45968,; ... 14:00, 6008, 45968, 4+8+5+27+29<60; ... Wh, 8000; 3+7+26+28<1500; </P2>
P3	MM	APC	Define Load Schedule	State and priority of each load for each time step	; T0, T1, ..., Tn; Load #, time interval 1 priority, ... , time interval n priority; ...	<P3> ; 12:00, 12:30, ..., 19:00; 1, ..., 14, 18, ...; 2, ..., 24, ..., 48, ...; 30, 18, ..., 21, ...; </P3>
P4	APC	MM	Determine Feasibility	Communicate detected conflicts	Time (hh:mm), new constraint; ...	<P4> 18:30, 3+4+5+6<60; </P4>
P5	MM	APC	Decision	Inform APC that the plan should be implemented (otherwise replan)	Implement;	<P5> Implement; </P5>

Table 17. Summary of the Automated Communication Format between the MM and APC to determine the response to a power system disturbance.

Message	Initiator	Receiver	Purpose	Content	Format	Example
A1	APC	MM	Inform of Disturbance	Disturbance type, expected impact of disturbance	Format: Timestamp, disturbance, impact horizon;	<A1> 15:03, There was a disturbance,; 14:35, There was a disturbance, 14:53; </A1>
A2	MM	APC	Decision	No action (otherwise replan)	Format: No action;	<A2> No action; </A2>

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